Quarterly Progress and Performance Indicators Report:
Project Number and Title: 1.4 Electromagnetic Detection and Identification of Concrete Cracking in Highway Bridges
Research Area: Thrust 1: Transportation infrastructure monitoring and assessment for enhanced life.
PI: Tzuyang Yu (UMass Lowell)
Co-PI(s): N/A
Reporting Period: 06/05/2018 ~ 09/30/2025
Submission Date: 09/30/2025

Summary of the project:

We have accomplished the following capabilities from our research activities:

- Development of a set of laboratory specimens with artificial cracks and real cracks to collect radar images
- Development of a portable EM sensor
- Application of portable EM sensors on real highway concrete bridges
- Development of an image processing technique to analyze the electromagnetic (EM) scattering of concrete cracking
- Development of an algorithm to generate artificial cracks in brittle materials using fractals
- Development of a numerical technique to simulate the electromagnetic scattering
- Development of an electromagnetic database of radar images

Overview:
The primary focus of our research is to address the challenge of evaluating aging concrete bridges, both reinforced and prestressed, located in New England. We have developed a remote radar sensor capable of characterizing corroded reinforced concrete structures, as well as a predictive capability to generate artificial cracks and simulate radar images. Two types of EM sensors are used in this research; ground penetrating radar (GPR) and synthetic aperture radar (SAR). These two EM sensors are compared in Figures 1 and 2.

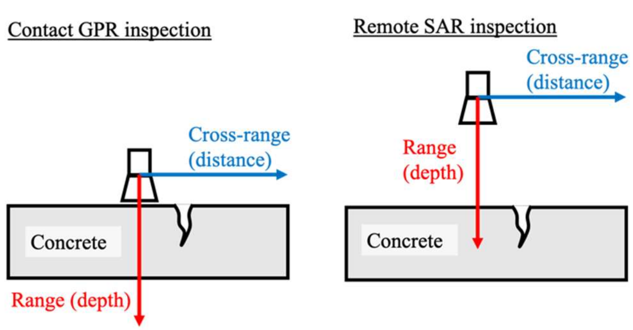


Figure 1. GPR and SAR inspection schemes

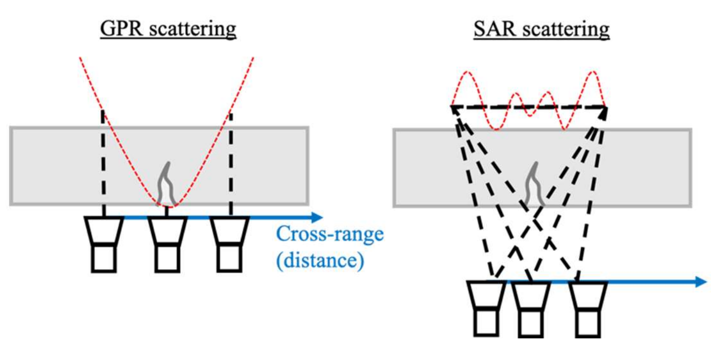


Figure 2. GPR and SAR scattering patterns of a crack

(a) Portable SAR sensor (b) Application of SAR sensor (c) Portable SAR imaging system

(d) Applications of GPR in the field

Figure 3. Portable SAR imaging sensor and portable GPR imaging sensor.

<u>Meeting the Overarching Goals of the Project:</u>

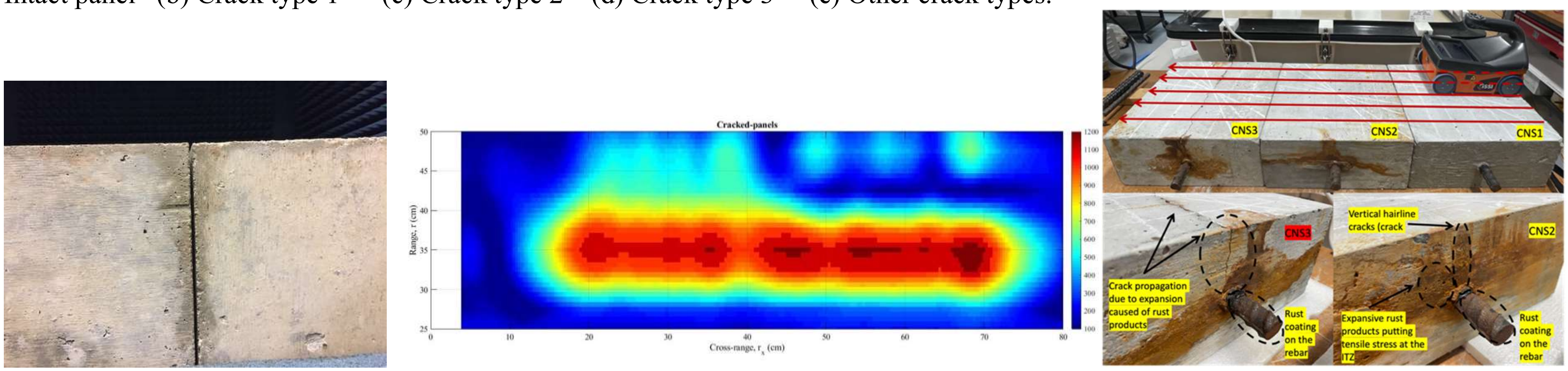
- Manufactured laboratory concrete and reinforced concrete specimens
- Conducted EM imaging of laboratory specimens
- Conducted field tests on highway concrete bridges in Massachusetts using portable EM sensors
- Developed solutions to analyze EM images for detecting concrete cracking

<u>Accomplishments:</u>

- We have designed ten concrete panel specimens with different artificial cracks to improve the accuracy in our study on the scattering effect of concrete cracking.
- We have manufactured ten concrete panel specimens with different artificial cracks to improve the accuracy in our study on the scattering effect of concrete cracking.

- We have collected more GPR B-scan images of intact and corroded concrete bridge abutment from one bridge on the Lowell Connector in Lowell, MA to study combined effect of concrete cracking and steel rebar corrosion.
- For field GPR B-scan images of cracked concrete bridge abutment, we have collected B-scan images containing scattering pattern of real concrete cracks.
- For field GPR inspection of cracked concrete bridge piers, we have identified a highway bridge in Chelmsford, MA for data collection.

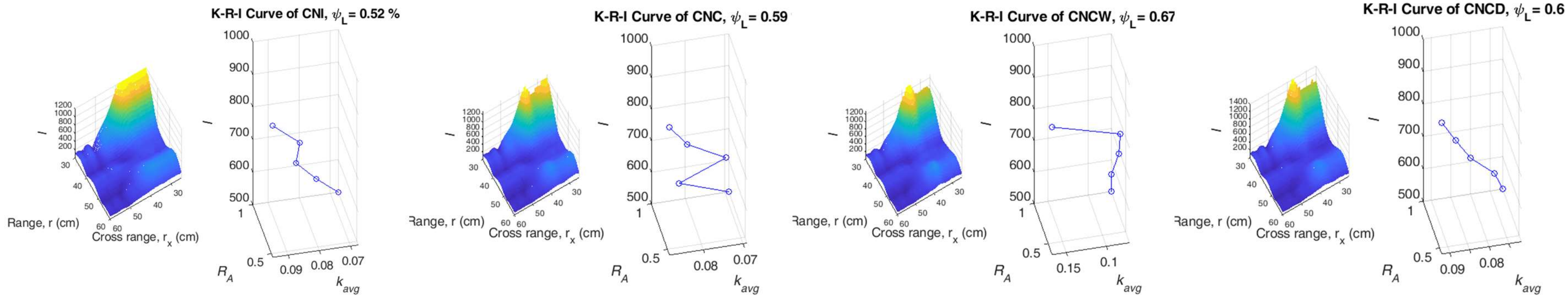
(a) Intact panel (b) Crack type 1 (c) Crack type 2 (d) Crack type 3 (e) Other crack types.



(f) Crack type 4 (g) Radar image of cracked panel – Crack type 4 (h) Corroded reinforced concrete specimens.

Figure 4. Laboratory concrete specimens.

- Development of an image processing technique to analyze the electromagnetic scattering of concrete cracking



(a) Specimen CNI – Intact (b) Specimen CNC – Standard crack. (c) Specimen CNCW – Crack with increased width (d) Specimen CNCD – Crack with increased depth

Figure 5. K-R-I transforms of SAR images of intact and damaged concrete panels

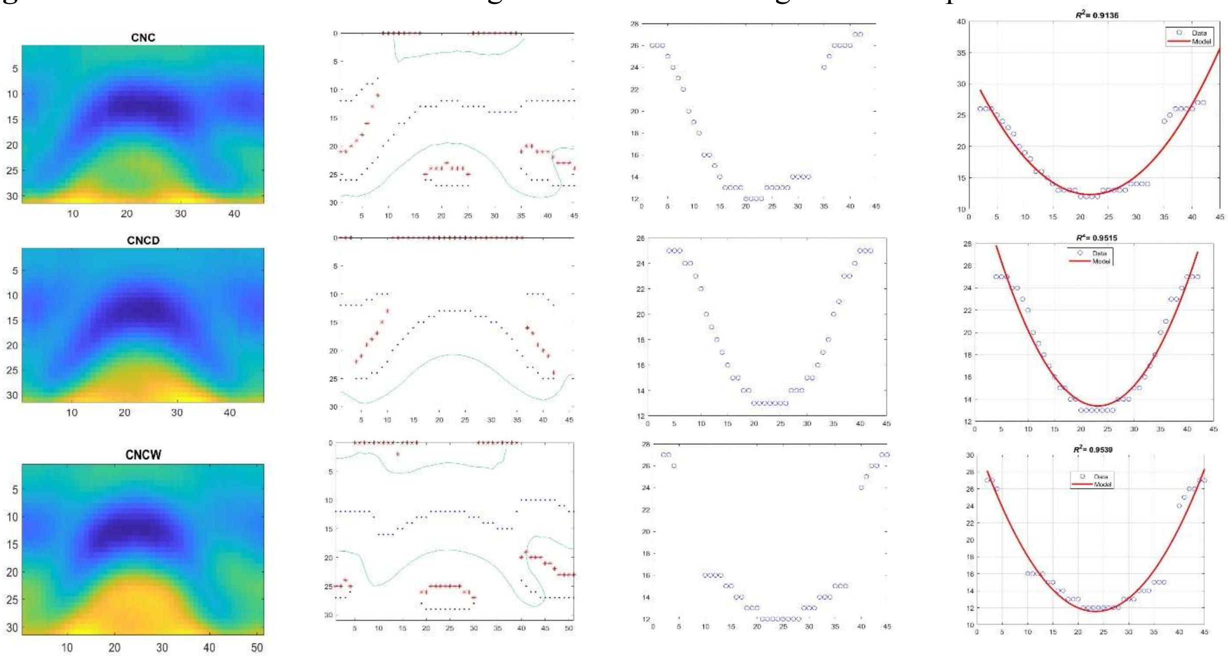
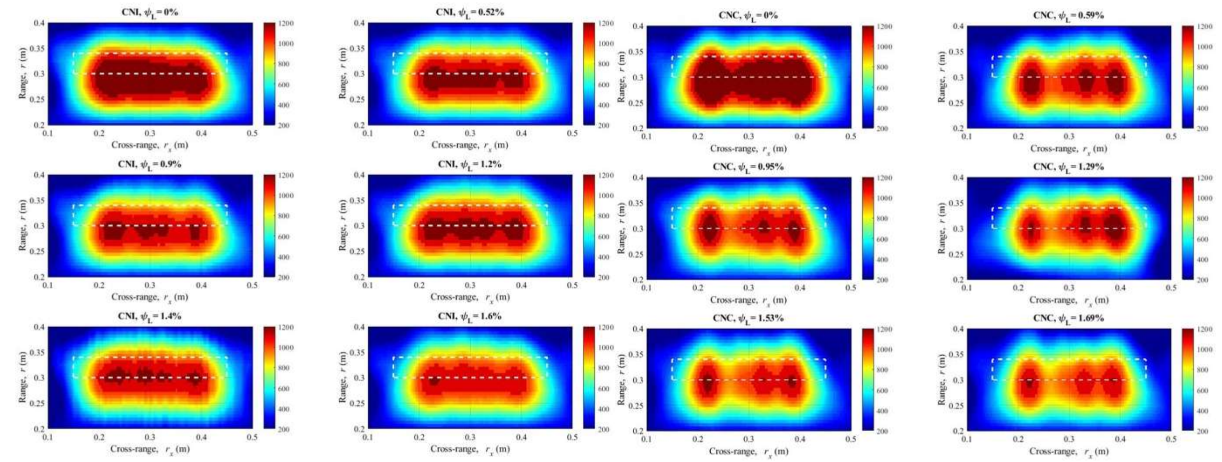
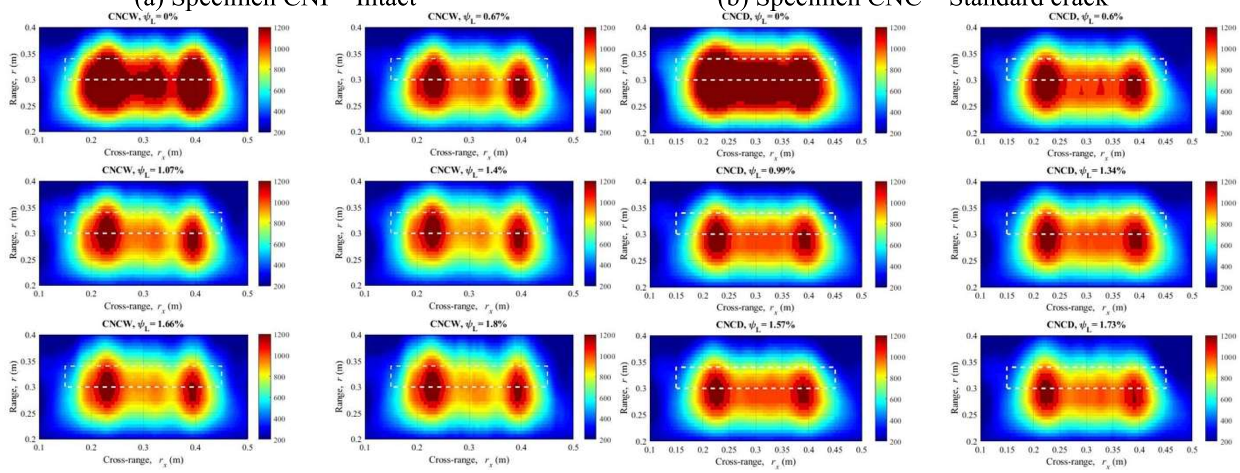


Figure 6. K-R-I transforms of SAR images of intact and damaged concrete panels

- Development of an electromagnetic database of radar images



(a) Specimen CNI – Intact (b) Specimen CNC – Standard crack



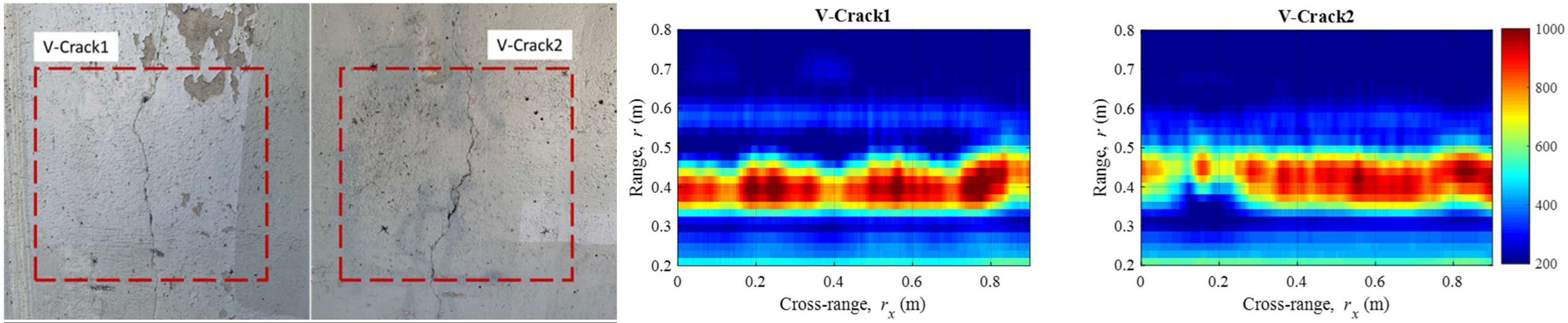
(c) Specimen CNCW – Crack with increased width (d) Specimen CNCD – Crack with increased depth

Figure 7. SAR images of intact and damaged concrete panels at various moisture levels

- Inspected highway bridges in Massachusetts

(a) Lincoln Street Bridge (b) Chelmsford I-495 bridge (c) Route 3 Lowell Connector in Lowell

Figure 8. Lincoln Street Bridge, Lowell, MA



(a) Vertical crack 1 (b) Vertical crack 2. (c) Radar image of vertical crack 1 (d) Radar image of vertical crack 2

Figure 9. Intact region and cracked regions in the field test

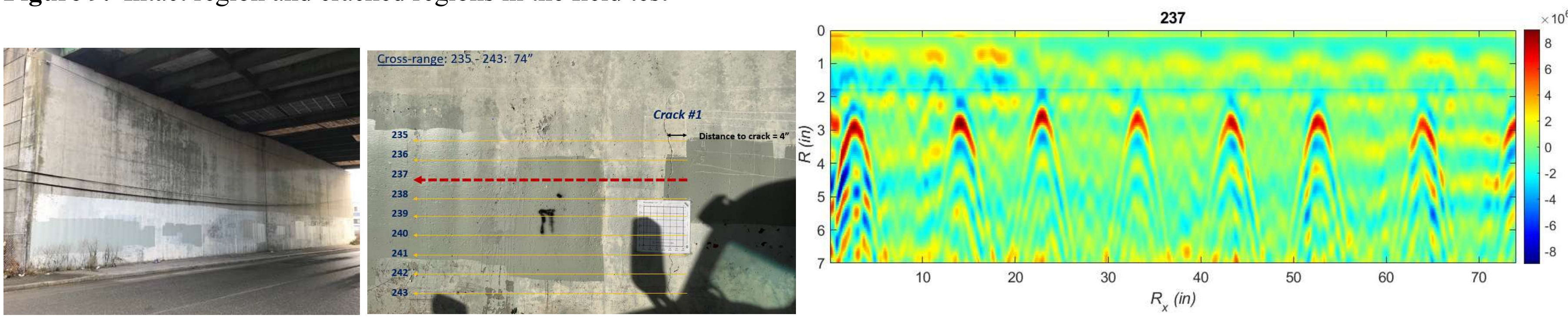


Figure 10. Lowell connector bridge abutment (Lowell, MA) and its GPR B-scan image (scan 237) with extracted pattern

- Development of an algorithm to generate artificial cracks in brittle materials using fractals

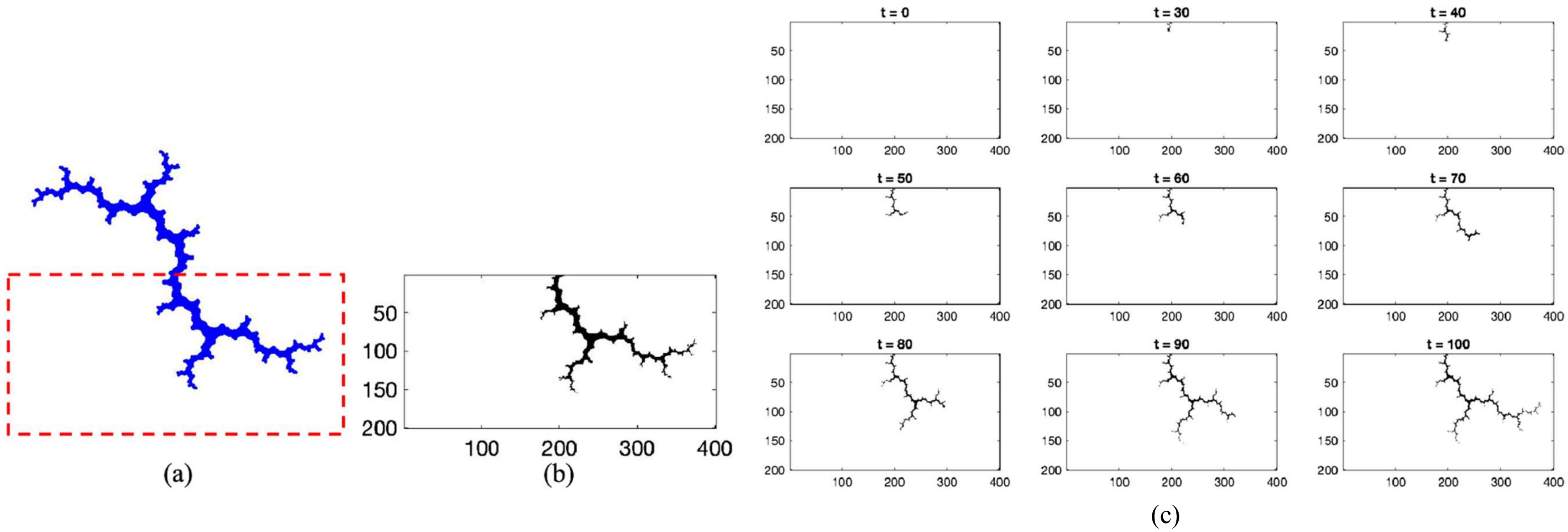
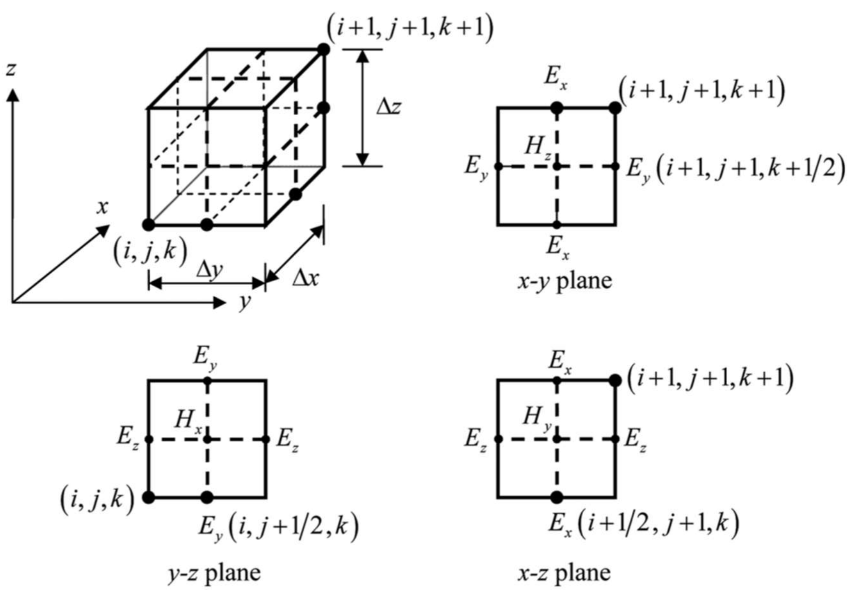
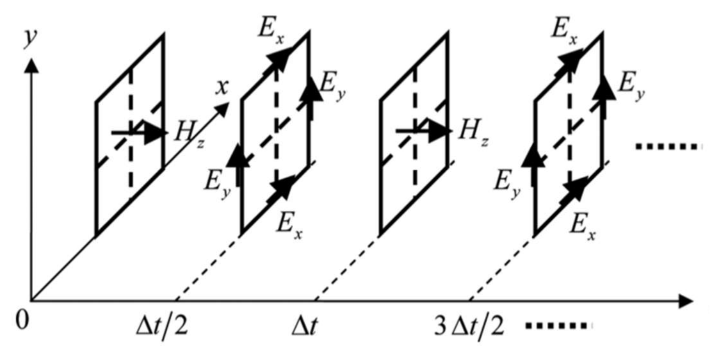


Figure 11. Development of artificial cracks using Julia set fractals.

- Development of a numerical technique to simulate the electromagnetic scattering

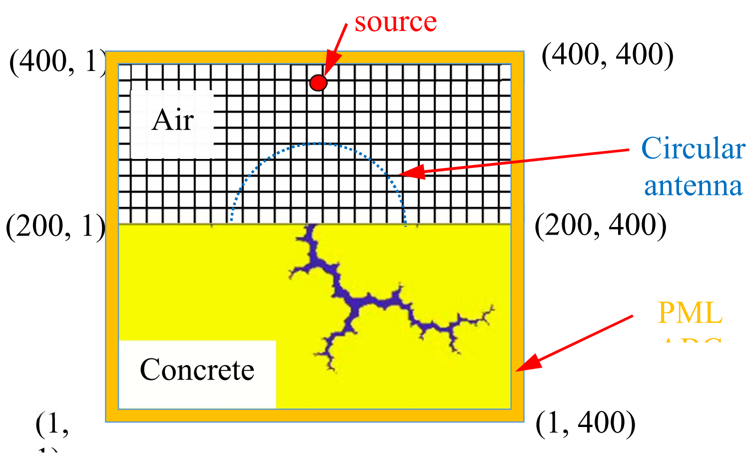


(a) The Yee discretization scheme.

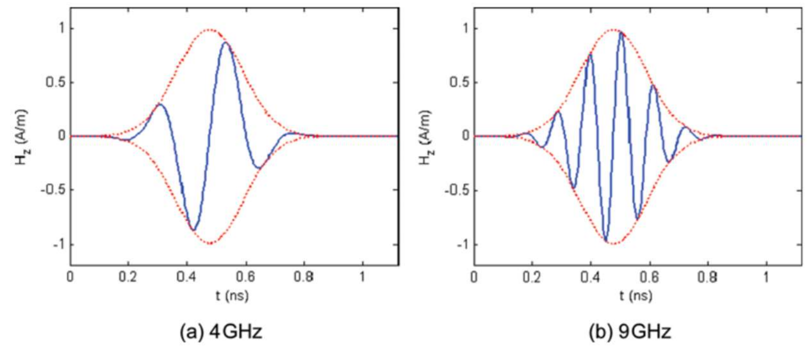


(b) Space-time leaping of electric and magnetic fields.

Figure 12. Evaluation of Maxwell's curl equations using the FDTD method.

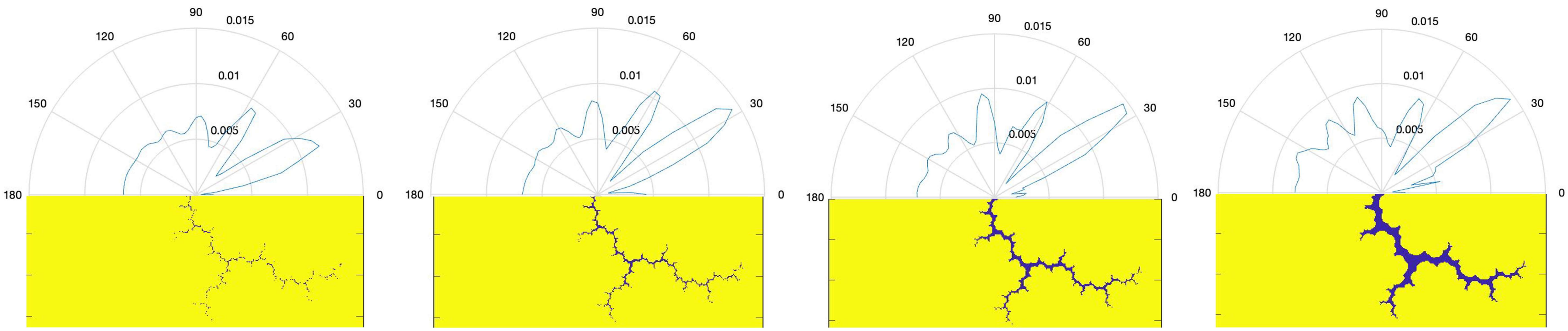


(a) Simulation domain.



(b) 4-GHz and 9-GHz modulated Gaussian signals.

Figure 13. Simulation domain and two simulated signals.



(a) Hair crack. (b) Small crack. (c) Medium crack. (d) Large crack.

Figure 14. Simulated cracks and their EM scattering response.

<u>Task, Milestone, and Budget Progress:</u>

Table 1: Task Progress			
Task Number: Title	**Start Date**	**End Date**	**% Complete**
Task 1: Design and manufacturing of laboratory reinforced concrete specimens at various corrosion levels	10/01/20	09/30/21	100%

Task 2: Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR/GPR image of concrete	10/01/21	09/31/22	100%
Task 3.1: Development of a compact, self-powered, light-weight SAR imaging sensor	10/01/21	05/31/22	100%
Task 3.2: Field inspection of corroded RC structures (Preliminary)	06/01/21	07/31/25	100%
Task 4: Development of EM database and correlation between SAR and GPR images	08/01/21	07/31/25	100%
Task 5: Data analysis and image interpretation	10/01/20	07/31/25	100%

Table 2: Milestone Progress

Milestone #: Description	Corresponding Deliverable	Start Date	End Date
Milestone 1: Design of laboratory reinforced concrete (RC) specimens at various corrosion levels	Experimentation design matrix; manufactured RC specimens; Quarterly report on 12/31/20	10/01/20	12/31/20
Milestone 2: Manufacturing of laboratory RC specimens at various corrosion levels / Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Development of a compact, self-powered, light-weight SAR imaging sensor	Manufactured RC specimens; SAR images of RC specimens; design of a compact SAR imaging sensor; Quarterly report on 03/31/21	11/01/20	03/31/21
Milestone 3: Manufacturing of laboratory RC specimens at various corrosion levels / Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Field inspection of corroded RC structures (Preliminary)	Manufactured RC specimens; SAR images of RC specimens; Development of a compact SAR imaging sensor; Preliminary SAR imaging of RC specimens in the field; Quarterly report on 06/30/21	12/01/20	06/30/21
Milestone 4: Manufacturing of laboratory RC specimens at various corrosion levels / Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Field inspection of corroded RC structures (Preliminary)	Manufactured RC specimens; SAR images of RC specimens; Preliminary SAR imaging of RC specimens in the field; Quarterly report on 09/30/21	12/01/20	09/30/21
Milestone 5: Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Field inspection of corroded RC structures (Preliminary)	SAR images of RC specimens; Preliminary SAR imaging of RC specimens in the field; Quarterly report on 12/31/21	12/01/20	12/31/21

Milestone 6: Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Field inspection of corroded RC structures (Preliminary)	SAR images of RC specimens; Preliminary SAR imaging of RC specimens in the field; Quarterly report on 03/31/22	12/01/20	03/31/22
Milestone 7: Laboratory SAR imaging of corroded RC specimens and development of a robust baseline SAR image of concrete / Field inspection of corroded RC structures (Preliminary)	SAR images of RC specimens; Preliminary SAR imaging of RC specimens in the field; Quarterly report on 09/30/22	12/01/20	09/30/22
Milestone 8: Field inspection of corroded RC structures	SAR imaging of RC specimens in the field; Quarterly report on 07/31/25	10/01/22	07/31/25
Milestone 9: Field inspection of corroded RC structures	SAR imaging of RC specimens in the field; Quarterly and Final reports on 07/31/25	10/01/22	07/31/25

Table 3: Budget Progress		
Project Budget	**Spend – Project to Date**	**% Project to Date (include the date)**
$582,995.97 (federal and match)	$582,995.97 (federal and match)	100% (federal and match)

Is your Research Project Applied or Advanced?

☒ **Applied** (*The systematic study to gain knowledge or understanding necessary for determining the means by which a recognized and specific need may be met.)*

☐ **Advanced** *(An intermediate research effort between basic research and applied research. This study bridges basic (study to understand fundamental aspects of phenomena without specific applications in mind) and applied research and includes transformative change rather than incremental advances. The investigation into the use of basic research results to an area of application without a specific problem to resolve.)*

Education and Workforce Development:

1. Did you provide any workforce development or training opportunities to transportation professionals (already in the field)? If so, what was the training? When was it offered? How many people attended?
   N/A

2. Did you hold meetings with any transportation industry organizations or DOTs? If so, what was the meeting's purpose? When was it offered? How many people attended?
   N/A

3. Did you host/participant in any K-12 education outreach activities? If so, what was the activity? What was the target age/grade level of the participants? How many students/teachers attended? When was the activity held?

Yes. We demonstrated our research in a number of Open House events to K-12 students. The total number of K-12 students visited our lab is estimated to be more than 200 students during 2018~2025. The total number of teachers visited our lab is estimated to be 15 during 2018~2025. The activity was held in our lab in Southwick Hall 130 at UML.

Technology Transfer:

Table 4: Presentations at Conferences, Workshops, Seminars, and Other Events

Type	Title	Citation	Event & Intended Audience	Location	Date(s)
Conference presentation	Assessing the Effect of Inspection Angle on Corrosion and Crack Detection in Reinforced Concrete Structures by using 1.6 GHz GPR	SPIE Smart Structures/Nondestructive Evaluation (SS/NDE) Symposium	International conference / academia (faculty and students), government industry	Vancouver, Canada	March 19, 2025
Conference presentation	Numerical Simulation of Artificial Cracks in Concrete Structures for Damage Detection	SPIE Smart Structures/Nondestructive Evaluation (SS/NDE) Symposium	International conference / academia (faculty and students), government industry	Vancouver, Canada	March 18, 2025
Seminar talk	Remote Bridge Health Monitoring using Laser Doppler Vibrometry and Imaging Radar	Tzuyang Yu, Department of Civil Engineering, National Central University (NCU)	Invited seminar / Undergraduate and graduate students in Civil Engineering	Chungli, Taiwan	October 25, 2023
Conference paper abstract	Assessing the Effect of Inspection Angle on Corrosion and Crack Detection in Reinforced Concrete Structures by using 1.6 GHz GPR	Maryam Abazarsa, Tzuyang Yu	International conference / academia (faculty and students), government industry	Long Beach, CA	September 30, 2024
Conference paper abstract	Identification of mechanical properties of portland cement concrete specimens using synthetic aperture radar, ultrasonic pulse	Maryam Abazarsa, Koosha Raisi, Tzuyang Yu	International conference / academia (faculty and students), government industry	Long Beach, CA	December 11, 2023

	velocity, and a rebound hammer				
Conference paper abstract	Corrosion detection of steel-reinforced concrete specimens using synthetic aperture radar	Koosha Raisi, Maryam Abazarsa, Tzuyang Yu	International conference / academia (faculty and students), government industry	Long Beach, CA	December 11, 2023
Conference paper abstract	Effects of moisture and chloride content on critical contour area in synthetic aperture radar images	Ahmed Alzeyadi, Tzuyang Yu	International conference / academia (faculty and students), government industry	Long Beach, CA	December 11, 2023
Seminar talk	Structural Engineering Research for Highway Bridges	Simpson, Gumpertz, and Heger (SGH)	Graduate students, engineers, managers	Waltham, MA	June 29, 2023
Conference paper abstract	Application of remote ground-penetrating radar for condition assessment of wooden crossties	Koosha Raisi, Ritham Batchu, Tiana Robinson, Tzuyang Yu, SPIE Smart Structures/NDE Symposium	International conference / academia (faculty and students), government industry	Long Beach, CA	September 12, 2023
Conference paper abstract	Effects of Moisture and Chloride Content on Critical Contour Area in Synthetic Aperture Radar Images	Ahmed Alzeyadi, Tzuyang Yu	International conference / academia (faculty and students), government industry	Long Beach, CA	September 14, 2023
Seminar talk	Noncontact Quantification of Chloride Ion Content in Concrete Specimens using Radar Images	Department of Mechanical and Materials Engineering, Worcester Polytechnic Institute (WPI)	Research seminar & WPI faculty and graduate students	Worcester, MA	March 30, 2023
Conference paper	Denoising of GPR B-scan Images using Discrete Wavelet Transform	doi:10.1117/12.2657741	International conference / academia (faculty and students), government industry	Long Beach, CA	May 9, 2023
Conference paper	Detection of steel rebar corrosion in bridge	doi: 10.1117/12.2657731	International conference / academia	Long Beach, CA	May 9, 2023

	piers using 1.6GHz ground penetrating radar		(faculty and students), government industry		
Conference paper	Remote detection of chloride ion content in concrete using SAR	doi:10.1117/12.2661309	International conference / academia (faculty and students), government industry	Long Beach, CA	May 9, 2023
Conference presentation	Interpretation of synthetic aperture radar images of concrete by combined uses of image parameters	Tzuyang Yu, Ahmed Alzeyadi, SPIE SS/NDE Symposium, Conference 12047 *Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XVI*	International conference & Academics, practitioners, government officials	Long Beach, CA	March 8, 2022
Conference presentation	Application of dual-frequency GPR for subsurface void detection in culverts	Koosha Raisi, Nimun Nak Khun, Tzuyang Yu, SPIE SS/NDE Symposium, Conference 12047 *Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XVI*	International conference & Academics, practitioners, government officials	Long Beach, CA	March 8, 2022

Table 5: Submitted/Accepted Publications, Technical Reports, Theses, Dissertations, Papers, and Reports

Type	Title	Citation	Date	Status
Journal paper	Multiphysical Characterization for Predicting Compressive Strength of Portland Cement Concrete using Synthetic Aperture Radar, Ultrasonic	Maryam Abazarsa, Tzuyang Yu / Scientific Reports, *Sci Rep* **15**, 6058 (2025). https://doi.org/10.1038/s41598-024-83829-y	February 18, 2025	Published

	Testing, and Rebound Hammer			
Journal paper	A Deep Learning Approach for Predicting Steel Rebar Corrosion in Concrete Bridge Columns from Two-Year Noisy GPR B-scan Images	Maryam Abazarsa, Tzuyang Yu /Case Studies in Construction Materials, Maryam Abazarsa, Tzuyang Yu, Case Studies in Construction Materials, 2025, e05671, ISSN 2214-5095, https://doi.org/10.1016/j.cscm.2025.e05671	December 2025	Published
Conference paper	Assessing the Effect of Inspection Angle on Corrosion and Crack Detection in Reinforced Concrete Structures by using 1.6 GHz GPR	Maryam Abazarsa, Tzuyang Yu, Proceedings Volume 13436, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIX; 134360R (2025) https://doi.org/10.1117/12.3051445	June 20, 2025	Published
Conference paper	Numerical Simulation of Artificial Cracks in Concrete Structures for Damage Detection	Tzuyang Yu, Albert Paradis, Maryam Abazarsa, Proceedings Volume 13436, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIX; 134360E (2025) https://doi.org/10.1117/12.3051576 Event: SPIE Smart Structures + Nondestructive Evaluation, 2025, Vancouver, B.C., Canada	June 20, 2025	Published
Peer-reviewed journal	Remote characterization of chloride content in concrete specimens using synthetic aperture radar images	Construction and Building Materials, Volume 302, 124317, doi: 10.1016/j.conbuildmat.2021.124317	4 October, 2021	Published

Answer the following questions (N/A if there is nothing to report):

1. Did you deploy any technology during the reporting period through pilot or demonstration studies as a result of this work? If so, what was the technology? When was it deployed?
   N/A

2. Was any technology adopted by industry or transportation agencies as a result of this work? If so, what was the technology? When was is adopted? Who adopted the technology?
   N/A

3. Did findings from this research project result in changing industry or transportation agency practices, decision making, or policies? If so, what was the change? When was the change implemented? Who adopted the change?
   N/A

4. Were any licenses granted to industry as a result of findings from this work? If so, when? To whom was the license granted?
   N/A

5. Were any patent applications submitted as a result of findings from this research? If so, please provide a copy of the patent application with your report.
   N/A

6. Did industry organizations or DOTs provide cost-share (cash or in-kind) to your research during the reporting period? Who was the organization? Please provide an in-kind support invoice from the organization with your report (this is kept confidential and used for record keeping purposes only).
   Yes. We received cost share contributions from industry partners (GSSI and MIDAS IT)

Outputs:

- An algorithm has been used to distinguish concrete cracking and steel rebar corrosion in RC structures.
- A fractal-based crack simulation approach has been used to generate simulated EM scattering response for solving the inverse problem.
- New image interpolation algorithm has been developed.
- New GPR B-scan images have been included to our EM database for the nondestructive inspection of concrete cracking.

Outcomes:

- The developed EM sensing technology was applied to three bridges in Massachusetts (Two in Lowell, one in Chelmsford) during 2018 and 2025 on a number of dates. We successfully applied a portable 10GHz SAR imaging sensor on these bridges to develop EM database. I also included our findings in my graduate course CIVE.5110 Inspection and Monitoring of Civil Infrastructure for training. We also successfully applied two GPR imaging sensors at different frequencies (300MHz/800MHz and 1.6GHz) in the City of Lowell and on three bridges in Massachusetts. Furthermore, we made many presentations at domestica and international conferences and industry, as well as publishing journal and conference papers to disseminate our research result.

Impacts:

- **Improved Transportation Safety and Monitoring**
  The development of our EM imaging capabilities has enabled the industry to use radar images to detect concrete cracking due to overstressing and steel rebar corrosion for early detection of damages. This allows the MassDOT to improve the accuracy of bridge inspection and transportation safety. From our field tests on three concrete bridges (I-495 Chelmsford Bridge, Route 3 Lowell Connector Bridge, and Lincoln Street Bridge), our research also provides state DOTs and the industry a technical solution for long-term bridge health monitoring.

- **Contribution to Knowledge and Technology Development**
  Our research findings obtained from physical experimentation, numerical simulation, and algorithm development have contributed to the knowledge and technology development in several areas, including near-field and far-field electromagnetic scattering between brittle dielectrics with regular and irregular cracks, generation of irregular cracks using Julia set fractals, and time-domain and frequency-domain simulation of electromagnetic scattering. Our findings have resulted in several journal papers and manuscripts. We also have presented our findings every year in an international conference, as well as presenting our research in invited seminars.
- **Education and Workforce Development**
  We have hosted more than 200 high-school students during 2018~2025 in many Open House events and lab visits on the use of EM sensing for construction materials and civil infrastructure systems. We also demonstrated the use of EM sensors to high school students in their visits to promote the user-experience of EM sensing on construction materials. Graduate and undergraduate students learned the laboratory and field application of EM sensors from our research activities in a senior-graduate level course CIVE.5110 Inspection and Monitoring of Civil Infrastructure. These educational activities can better prepare the students for the next-generation workforce in transportation industry.
- **Enhanced Research Infrastructure**
  Our collaboration with the state DOTs, industry (GSSI, Kiewit Corporation) and municipalities (City of Lowell) connected end-users with equipment vendors through our research activities. End-users gained more understanding on the characteristics of commercially available EM sensors (e.g., GPR) and the potential of novel EM sensors (e.g., SAR).

Participants and Collaborators:

Table 6: Active Principal Investigators, faculty, administrators, and Management Team Members

Individual Name & Title	Dates involved	Email Address	Department	Role in Research
Tzuyang Yu		Tzuyang_Yu@UML.EDU	Civil and Environmental Engineering	Project principal investigator and Institutional Lead at UML; overseeing all projects and working on radar imaging and interpretation

Table 7: Student Participants during the reporting period

Student Name	Start Date	End Date	Advisor	Email Address	Level	Major	Funding Source	Role in research
Maryam Abazarsa	4/1/25	6/30/25	Prof. Yu	Maryam_Abazarsa@student.uml.edu	Ph.D.	Civil and Environmental Engineering	TIDC	Laboratory specimen design and manufacturing, data processing and analysis, field data collection

Table 8: Students who Graduated During the Reporting Period			
Student Name	**Degree/Certificate Earned**	**Graduation/Certification Date**	**Did the student enter the transportation field or continue another degree at your university?**

Table 9: Industrial Internships			
Student Name	**Degree/Certificate Earned**	**Graduation/Certification Date**	**Did the student enter the transportation field or continue another degree at your university?**
Shrilekha Medarapu	Master's degree	6/30/25	TranSystems Corporation (Boston, MA)

Table 10: Research Project Collaborators during the reporting period						
Organization	**Location**	**Contribution to the Project**				
		Financial Support	**In-Kind Support**	**Facilities**	**Collaborative Research**	**Personnel Exchanges**
MassDOT	Boston, MA				X	X
City of Lowell	Lowell, MA	X			X	X
Geophysical Survey Systems, Inc. (GSSI)	Nashua, NH				X	X

Table 11: Other Collaborators				
Collaborator Name and Title	**Contact Information**	**Organization and Department**	**Date(s) Involved**	**Contribution to Research**
Gregory Krikoris	Gregory.Krikoris@state.ma.us	MassDOT		Technical champion
Mark Jen	Mark.Jen@kiewit.com	Kiewit Corporation		Technical champion

Number of active industrial partners involved in this research project
One

Number of technical Champions actively involved in this project:
Two

Table 12: Course List

Course Code	Course Title	Level	University	Professor	Semester	# of Students
CIVE.5110	Inspection and Monitoring of Civil infrastructure	Senior/Graduate	UML	Tzuyang Yu	Fall 2025	35
ENGN.2070	Dynamics	Sophomore	UML	Tzuyang Yu	Fall 2025	50

Changes:
N/A

Planned Activities:
N/A